Experimental study of base stabilization with fibrillated fiber

Dar Hao Chen^{a*}, Younho Rew^a, Anand Bajarang Tapase^b, William Crockford^a

^a Texas A&M Transportation Institute, 3135 TAMU, College Station, Texas, USA

^b RayatShikshanSanstha's, KarmaveerBhauraoPatil College of Engineering, Satara, India

Received 13 November 2020; received in revised form 20 November 2020; accepted 23 November 2020

Abstract

Potential benefits in applying polypropylene fiber to stabilize expansive soils and cement treated bases is already been reported in previous studies. So a critical need exists to incorporate the use of fiber into the Texas Department of Transportation's (TxDOT's) Guidelines for Modification and Stabilization of Soils and Base for Use in Pavement Structures. The present paper discusses the results collected from the first experimental test section on FM897 in the TxDOT Paris District. Three 500-ft (152.4m) test sections were constructed with 2 percent cement on FM897 in February 2020 in the north bound lane loaded truck direction which includes a new sandstone base, full depth reclamation (FDR), and control. However, only the new sandstone base and FDR sections were built with fiber. In this project, two types of fibers were used—(a) fibrillated fiber Fibermesh300, and (b) macro-synthetic fiber Enduro 600. The surface and base layers from the new sandstone base section were removed and used for the edge widening area of the FDR and control sections. Based on the laboratory tests, the optimum fiber contents were found to be 0.6 percent and 0.4 percent for a new sandstone base and FDR, respectively. The laboratory Unconfined Compression Strength (UCS) results showed significant improvements (>112.36 percent) when fibers were added to the sandstone base. To have better control, fiber and cement were manually distributed, following the US Army Corps of Engineers' recommendations. Because of unexpected construction equipment failure that caused compaction delays of approximately 5 hours, cement was in contact with moisture for approximately 5 hours before compaction. UCS results showed an approximate 55 percent reduction when there was a 5-hour delay from the time water was introduced (resulting in the start of the hydration process) until the time of compaction. It indicated that there are detrimental effects on UCS if there is delay on compaction. There were significant reductions on the normalized W1 deflections at 5 months after construction. In particular, the FDR and new sandstone base sections (with fiber) experienced over 52 percent reduction as compared to 1 week after construction FWD data. Furthermore, the averaged W1 deflections were lower than before construction for both FDR and new sandstone base sections (with fiber). This indicates that there were rapid increases in structural capacity and significant strength developed in the fiber sections between 1 week and 5 months. Further research is needed to explain the mechanism and phenomena.

Keywords: Soil Stabilization; Cement-Treated Base; Polypropylene Fibers; FWD

1. Introduction

Number of researchers has efficiently used various additives like Sawdust ash, quarry dust and Portland cement, sisal fiber, lime-fly ash, etc to improve the performance of expansive soils [1,2]. Research results from earlier study indicate that the polypropylene fiber-reinforced, cement-treated base improves performance and extends pavement life [3–10]. Hereafter, polypropylene fiber is referred to as fiber in this document. Significant improvements in shear and compressive strengths, as well as flexibility, have been reported in fiber-reinforced, cement-treated bases. Also, fiber-

reinforced clays and sands were able to reduce volumetric shrinkage strains and swell pressures. Huge potential benefits exist in applying fiber to stabilize expansive soils and cement-treated bases to (a) increase strength, (b) reduce shrinkage potential, (c) reduce chemical stabilizer content, and (d) increase flexibility/ductility. Thus, a critical need exists to incorporate the use of fiber into the Texas Department of Transportation's (TxDOT's) Guidelines for Modification and Stabilization of Soils and Base for Use in Pavement Structures. The present paper discusses the results collected from the first experimental test section on FM897 in the TxDOT Paris District.

The pavement width on FM897 before reconstruction was approximately 10-ft (3m) wide. Fig. 1 shows the existing pavement conditions before reconstruction. There were severe ruts of more than 4inches (102mm), shoveling, and patches in the project alignment. Existing materials from FM897 were retrieved for laboratory testing, as shown in Fig. 2. To minimize pavement edge failure, the pavement width for the test sections was widened to 12 ft (3.66m) three 500-ft (152.4m) test sections were constructed in

* Corresponding author

E-mail address: d-chen@tti.tamu.edu (D. H. Chen); y-rew@tti.tamu.edu (Y. Rew); tapaseanand@gmail.com, <https://orcid.org/0000-0002-4560-3564> (A. B. Tapase); w-crockford@tti.tamu.edu (W. Crockford).

Peer review under responsibility of Chinese Society of Pavement Engineering.

ISSN: 1997-1400 DOI: <https://doi.org/10.1007/s42947-020-6005-6>
Chinese Society of Pavement Engineering. Production and hosting by Springer Nature

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Fig. 1. and Pavement Condition for FM897.

Fig. 2. Retrieval of existing roadbed for lab testing.

the northbound lane direction, which is the loaded truck direction. The three 500-ft (152.4m) test sections were built in February 2020 and included (a) a new sandstone base, (b) full depth reclamation (FDR), and (c) control. The surface and base layers from the new sandstone base section were removed and used for the edge widening area of the FDR and control sections. All three sections were constructed with 2 percent cement. However, only the new sandstone base and FDR sections were built with fiber. Based on the laboratory tests, the optimum fiber contents were found to be 0.6 percent and 0.4 percent for a new sandstone base and FDR, respectively. The FDR section in this tech memo indicates existing material from FM897 mixed with 2 percent cement and fiber.

Fibermesh 300 was used in both test sections because the cost of Enduro 600 was about twice (200 percent) that of Fibermesh 300. Laboratory unconfined compression strength (UCS) test results did not show that specimens with Enduro 600 were significantly better than those with Fibermesh 300. Fibermesh 300 is one of the fibrillated fibers suggested by the US Army Corps of Engineers [11-16]. The control section was a conventional reworking of the existing roadbed with 2 percent cement. The Paris District has specified 2 percent cement for all FDR and cement-treated base projects. Fig. 3 presents the layout of three test sections and distribution grids for fiber and cement.

All three sections were applied with a seal coat on March 5, 2020. However, between February 27 and March 5, there were about 1.27 inches (32.25mm) of rain in the area. The seal coat applied on March 5, 2020, consisted of RC 250 and Grade 4 aggregates. The high potential existed for moisture to have entered newly constructed fiber-reinforced cement sections before the seal coat was applied. Approximately 6,081 lb (2758 kg) of fibers

(Fibermesh 300) were used for two 500-ft (152.4m) by 12-ft (3.658m) by 10-inch (254mm) sections. About 90,000 lb (40,824kg) of cement were used for three 500-ft (152.4m) by 24-ft (7.32m) by 10-inch (254mm) sections. The quantity of new sandstone base was approximately 185.2 CY (500-ft (152.4m) by 12-ft (3.658m) by 10-inch (254mm)). The test sections were constructed by a TxDOT in-house maintenance crew using an RM-250C reclaimer/mixer, as shown in Fig. 4.

Details of construction and monitoring of test sections are presented in the following sections.

2. Fiber applications rates through laboratory testing

It has been reported that a combination of chemical stabilizers with fibers yields better strength results [5-8]. Fibers need cement or other chemical stabilizers in order to bond and to interlock with

1ft=0.3048 m, inch=25.4mm

Fig. 3. Layout of test sections and fiber and cement distribution grids.

Mixing Chamber and Rotor

Assures depth control, proper sizing and thorough blending of materials.

Fig. 4 RM-250C reclaimer/mixer used for FM897 test construction.

surrounding soil/aggregate to activate tensile strength benefits. Cement can also form a matrix to get additional adhesion to surrounding particles from fiber, so the flexibility is increased beyond a soil/aggregate with fiber only. Fiber in a soil/aggregate base is a primary source of resistance of tension when it is stressed because fiber is bonded to particles due to fiber-particle contact. In this project, two types of fibers were used—(a) fibrillated fiber Fibermesh300, and (b) macro-synthetic fiber Enduro 600—as shown in Fig. 5. The top fiber shown in the Fig. is Fibermesh300, and the bottom one is Enduro 600. Enduro 600 is displayed with a unique length of 2inches. Basic physical and chemical properties of the two fibers can be found in Table 1 and Table 2.

2.1. Laboratory testing to determine optimum fiber content

In order to examine the effects of different combinations of fibers and cement, different fiber contents (from 0.0 percent to 1.0 percent) and cement amounts (1.0percent and 3.0 percent) were evaluated, as illustrated in Table 3 a total of 35 specimens were prepared. After mixing, both type of fibers seemed to be uniformly distributed in the mixture at low volume contents, but a significant amount of fiber clumps was found when the Fibermesh300 content exceeded 0.6 percent or the Enduro 600 content exceeded 0.75 percent. The initial plan was to use a Superpave gyratory compactor to prepare UCS specimens. However, problems began

Fig. 5. Fibermesh 300 and Enduro 600.

Table 1
Chemical and Physical Properties of Fibermesh 300 [17].

Absorption	Nil	Melt point	162 °C
Specific gravity	0.91	Ignition point	593 °C
Fiber length	Graded	Thermal conductivity	Low
Electrical conductivity	Low	Alkali resistance	Alkali proof
Acid & salt resistance	High		

Table 2
Chemical and Physical Properties of Enduro 600 [18].

Absorption	Nil	Melt Point	164 °C
Specific gravity	0.91	Ignition point	550 °C
Fiber length	50 mm	Thermal conductivity	Low
Electrical conductivity	Low	Alkali resistance	Alkali proof
Acid & salt resistance	High	Equivalent diameter	0.77 mm

Fig. 6 Mixing and compacting problems on base materials at high fiber content.

Table 3
Parametric study.

Material	Cement-Treated Base Mixture (without Fiber)	Fibermesh 300	Enduro 600	Cement
New Sandstone	Control	0.4%	N.A.	1.0%
	Control	0.2%, 0.4%, 0.6%, 0.8%	0.25%, 0.50%, 0.75%, 1.00%	2.0%
FM 897 Base	Control	0.2%, 0.4%, 0.6%, 0.8%	0.25%, 0.50%, 0.75%	2.0%
	Control	0.4%	N.A.	3.0%

to emerge during specimen preparation. The problems were much more severe for the Fibermesh 300 mixture than the Enduro600 at the high fiber contents because Fibermesh 300 is very thin and clumps together more easily, as shown in Fig. 6. Because of this issue, all specimens were compacted using a drop rammer—per ASTM D1557 specification. Each cylindrical specimen was 6 inches (152.4mm) in diameter and 8 inches (203.2mm) tall. All specimens were cured for 7 days in an environmentally controlled room with 100 percent relative humidity. After 7-day curing, specimens were capped with porous stone and subjected to UCS testing at a constant strain rate of 2 percent/minute. To capture the full-range stress-strain curve, testing was continued until an 80 percent drop point of maximum stressor 0.5-inch (12.7 mm) displacement was attained.

The results of the UCS tests conducted in this study are shown in Fig. 7 and Fig. 8. A total of 35 UCS specimens with fiber contents ranging from 0 percent to 1.0 percent were tested. Based on Fig. 7(a) and 8(a), after comparing the stress-strain curves from the UCS tests, it was determined that for specimens with higher

cement content, two tendencies were clear: higher peak compressive strength and higher compressive secant modulus of elasticity. In regard to fiber content, different trends were seen according to fiber type. With Fibermesh300, both base materials retained the maximum compressive stresses and moduli of elasticity in soil systems containing adequate amounts of fiber rather than the highest fiber content. Enduro 600 gave slightly different results from Fibermesh300. The maximum compressive stress values were at higher strain values than what was seen with Fibermesh300. This meant that Enduro600 made the soil mixture more ductile than did Fibermesh300, and the modulus of elasticity was lower than that of Fibermesh300. The UCS results in Figs. 7 and 8 show that significant improvements ($>>100$ percent) were observed when fibers were added.

Fig. 7. UCS test results of new sandstone base (Paris District) (a) New Sandstone Base with Fibermesh300 and (b) New Sandstone Base with Enduro600.

Fig. 8. UCS test results (a) FM897 base with Fibermesh300 and (b) FM897 base with Enduro600.

The fiber-reinforced specimens with two fiber types generally broke in small areas, while the control specimens had abrupt/rapid failures. The fiber samples always fell apart into different pieces, as shown in Fig. 9. This phenomenon clearly proved that fibers improve the ductile properties of aggregate base mixture. The benefits of fibers are activated when they are under tension. The ductility of fibers can be beneficial in mitigating premature cracking from the cement-treated base and in mitigating heaving/bump issues from expansive, sulfate-bearing, and/or organic rich subgrade soils. In addition, in the field, the use of fibers may allow for a reduction in chemical stabilizer content. The results of UCS tests are shown by a stress versus strain curve. The area under this curve is known as strain energy, or toughness. Toughness is a measure of the energy absorbed by the system per unit volume. The greater the toughness of a sample, the more energy it needs to achieve failure. The curve defining the behavior up to maximum strains beyond the strain at the peak load gives an indication of how severe performance degradation might be in that region. Typically, fibers in a cement-stabilized material will show better performance at strains beyond the strain at peak stress (i.e., a material with cement but no fiber will tend to fail at a more rapid rate than one that also contains fibers).

The toughness levels of the mixtures studied are shown in Fig. 10. Toughness is an energy method that has recently been used in decision-making, along with maximum compressive stress. In the present research, two toughness levels were calculated at the 4 percent and 5 percent strains. As Fig. 10 illustrates, the toughness calculated by the 4 percent and 5 percent strains showed a similar trend in all cases. The results of toughness analysis clearly display that the proper fiber content, along with the maximum compressive stress, has a positive effect on the mixture (Fig. 10). In the case of maximum compressive stress, Enduro 600 shows a continual increase in compressive stress as the amount of fiber increases in both base materials, as shown in Fig. 7 (b) and Fig. 8 (b). However, toughness clarifies the 0.75 percent fiber content of the Enduro600 as an optimum amount, especially in Paris District sandstone base materials. Overall, the optimum fiber contents of Fibermesh300 and Enduro600 were determined as 0.4 percent and 0.75 percent, respectively. Table 4 summarizes the analysis results of the UCS tests.

Fig. 9. UCS test specimens (a) new sandstone base with fibers and (b) FM897 base with fibers.

Fig. 10 Toughness Calculation (2% strain) (a) Paris district sandstone base with Fibermesh300, (b) Paris district sandstone base with Enduro600, (c) FM897 base with Fibermesh300, and (d) FM897 base with Enduro600.

Table 4
Summary of test results (1 psi = 0.0069 MPa).

Base material	Fiber type	Fiber amount	Cement amount	Toughness	Change in toughness for base,UCS including fibers relative to plain base material		Change in UCS for base, including fibers relative to plain base material
				psi (MPa)	(%)	psi (MPa)	(%)
Paris District Sandstone	—	0.00%	1.00%	6.36 (0.04)	—	180.5 (1.25)	—
		0.00%	2.00%	6.91 (0.05)	—	226.64 (1.56)	—
	Fibermesh300	0.20%	2.00%	12.89 (0.09)	86.55%	370.48 (2.56)	63.46%
		0.40%	1.00%	9.91 (0.07)	55.90%	271.03 (1.87)	50.16%
		0.40%	2.00%	11.48 (0.08)	66.15%	327.62 (2.26)	44.55%
		0.60%	2.00%	17.83 (0.12)	158.13%	481.3 (3.32)	112.36%
		0.80%	2.00%	10.12 (0.07)	46.52%	280.99 (1.94)	23.98%
		0.25%	2.00%	10.34 (0.07)	49.64%	306.24 (2.11)	35.12%
	Enduro600	0.50%	2.00%	13.77 (0.10)	99.27%	472.75 (3.26)	108.59%
		0.75%	2.00%	14.25 (0.10)	106.25%	434.2 (3.00)	91.58%
1.00%		2.00%	12.85 (0.09)	86.05%	500.9 (3.46)	121.01%	
FM 897	—	0.00%	2.00%	4.56 (0.03)	—	146.25 (1.01)	—
		0.00%	3.00%	5.63 (0.04)	—	204.01 (1.41)	—
	Fibermesh300	0.20%	2.00%	5.87 (0.04)	28.93%	163.02 (1.12)	11.47%
		0.40%	2.00%	7.83 (0.05)	71.81%	201.33 (1.39)	37.66%
		0.40%	3.00%	8.71 (0.06)	54.72%	238.83 (1.65)	17.07%
		0.60%	2.00%	7.43 (0.05)	63.16%	189.98 (1.31)	29.90%
		0.80%	2.00%	7.12 (0.05)	56.17%	184.29 (1.27)	26.01%
		0.25%	2.00%	6.61 (0.05)	45.10%	174.05 (1.20)	19.01%
	Enduro600	0.50%	2.00%	7.47 (0.05)	64.01%	193.97 (1.34)	32.63%
		0.75%	2.00%	8.41 (0.06)	84.61%	226.69 (1.56)	55.00%

3. Construction and test section monitoring

To have uniform distribution of cement and fiber for the test section, the first task is to develop the stabilization layout. The layout is comprised of lines and grids with markings that contain the distribution points for cement bags and fiber box placements

along traveling lanes. The fiber boxes and cement sacks were evenly distributed, as shown in Fig. 3 and Fig. 11. The spacing of the fiber and cement was determined by stabilization depth, fiber/cement content, density of compacted soil, mixing lane width, and size of the stabilization area.

The US Army Corps of Engineers [13,16] suggested that grading

Fig. 11. Manual Distribution of fiber and cement.

of the surface should be avoided unless absolutely necessary. Grading of fiber-stabilized surfaces may cause tearing of the soil/cement/fiber material. In this study, the test sections were graded and shaped to the approximated final elevation before constructing the test section to minimize grading after mixing with cement and fiber. Per the US Army Corps of Engineers' recommendation (Tingle et al. 1999; Webster and Santoni 1997), the fibers are best spread by tossing clumps of fibers onto the cement surface and letting them drift onto the surface, as shown in Fig. 11. Manual dispersing and raking were used to spread the fiber evenly, as Fig. 12 displays. An RM-250C was used as a mixer (see Fig. 12). Before dispersing the cement and fiber into the ground, efforts were made to ensure the moisture content of the existing base was approximately at optimum. A water truck was used to provide moisture needed to reach optimum moisture content for FM 897, as shown in Fig. 13. In order to measure the in-situ moisture content in real time, the moisture probe (GeneralmodelDSMM500) was used during test section construction (see Fig. 14). Fig. 14 illustrates how the moisture probe data were collected on FM897.

3.1. In-situ moisture measurement and control

The measurement range of this moisture probe (General model: DSMM500) is from 0 percent to 50 percent, with 0.1 percent

Fig. 12. Manual distribution of fiber and cement.

Fig. 13. Spreading water from water truck to reach optimum moisture content for FM 897.

Fig. 14 Real time in-situ moisture measurement in FM897.

resolution. The two-pin electrode in the system issued to measure the conductivity of the surrounding soil mixtures, and then the equipment converts the measurement to the reading of percent moisture content. For calibration, three FDR mixtures were used in the laboratory:

1. SH 6: 75 percent base + 25 percent Reclaimed Asphalt Pavement (RAP).
2. FM 117: 67 percent salvage base + 33 percent new base.
3. FM 3080: 69 percent Section 2 mix (base+RAP) + 31 percent Section 1 RAP.

Fig. 15 illustrates the trend lines that were color-coded to match the corresponding OMD/design samples. The R^2 values proved proper estimated moisture content on mixtures. Scheberl et al. (2019) documented that the General DSMM500 model was able to measure soil moisture contents reliably [19].

3.2. Field moisture content measurement and controls

For the new sandstone base test section, existing moisture content was measured at 2.7 percent. Based on laboratory test results, to reach the optimum moisture content of 6.7 percent, 5.31 gal/yd² (24.05 l/m²) of additional water was needed. Therefore, 3,539 gal (13397 liters) was added in the 500-ft (152.4m) test section to reach the optimum moisture content (OMC). After adding water, the moisture content at a 4-inch (102mm) depth from the base surface was 7.6 percent. The test section was mixed by the RM 250C, and then moisture content was measured at 8.5 percent. Note that all in-situ moisture content measurements using the General DSMM500 model were conducted at a depth of approximately 4 inches (102mm).

For the FDR test section, existing moisture content was measured at 7.7 percent. Based on laboratory test results, to reach

Fig. 15. Lab verification of DSMM 500 moisture content.

the OMC of 10.5 percent, 3.58 gal/yd² (16.22 l/m²) of additional water was needed. In this case, 2,389 gal (9042 liters) was added to the 500-ft (152.4m) test section to reach the OMC. After spreading water with the water truck, the moisture content at a 4 inches (102mm) depth from the FDR base surface was 9.85 percent. Compared to the new sandstone base test section, it appeared that the FDR section was denser. Therefore, additional water was needed. Approximately 500 gal (1893 liters) of water was added twice to the FDR test section. After that, in-situ moisture content reached the OMC of 10.5 percent. After mixing by the RM-250C, moisture content was measured at 10.3 percent.

For the control test section, approximately the same condition was required because of the same cement content and base layer depth. The main difference was the absence of fiber. The existing moisture contents were measured three times, and the average was 7.53 percent. Thus, 3.73 gal/yd² (16.90 l/m²) of additional water was needed. A total of 2,489 gal (9422 liters) was added to the 500-ft (152.4m) test section to reach the OMC of 10.5 percent. After spreading water, moisture content was measured at less than 10 percent. An additional amount of about 500 gal (1893 liters) of water was added, and the moisture content was measured at 10.6 percent. Therefore, in-situ moisture contents for the two fiber-reinforced base test sections and control sections were controlled at close to the OMC.

3.3. Test section compaction

The test sections were constructed by the TxDOT in-house maintenance crew using an RM-250C, a padfoot roller, a pneumatic roller, a bladder, and a steel roller, as shown in Fig. 16. The TxDOT in-house maintenance crew was composed of experienced equipment operators who do much of this construction by “feel,” and they know how it should feel while working the material.

3.4. Fiber-reinforced base sections: new sandstone base and FDR

Unfortunately, during test section construction, there was a hydraulic hose failure in the RM-250C that caused a delay of about 5 hours, which meant that cement was in contact with water for 5 hours. The US Army Corps of Engineers [3,13,14] indicated that under no circumstances should compaction be started more than 30 minutes after mixing.

The maximum setting for an RM-250C is 2,100 RPM. The RM-250C used was fairly old, so the operator did not want to push it to the max since one breakdown occurred due to the hydraulic hose failure mentioned above. It was observed that when the RM-250C was operated at 1,850 RPM, the fiber would not reach desirable expansion. Through adjustments, it was determined that when the RM-250C was set at about 2,000 RPM, one pass would be sufficient to reach desirable fiber mixing and expansion. In addition, the expansion of fiber was improved by slowing down the forward travel and/or by closing the rear gate on the drum housing a little bit on part of the job.

The sequences of compactions included two to three passes of the padfoot roller, two to three passes of the pneumatic roller, two passes of the maintainer blade (however, there were more than two passes for much of the job), and two to three passes of the steel roller. Fig. 17 illustrates the condition of the compacted surface. Note that no visible tearing of the surface occurred when a blade was used to smooth and improve the cross slope of the surface.

Fig. 16. Construction equipment used in FM897 test sections.

Fig. 17. Condition of compacted surface.

Thus, reworking the surface to obtain the final profile with a blade did not seem to present a significant problem, even though the Corps of Engineers' experience seemed to be less favorable, but this needs additional verification from other projects.

It is worth noting that a maximum windspeed of 25 mph was reported from the weather station during the construction of the test section. Although some fiber escaped, it was not a huge amount. Thus, the results suggested that construction of a fiber-reinforced base can be accomplished during windspeeds of up to 25 mph. 25 mph windspeeds may be included in the first version of specification. Future field construction information can be used for threshold value refinement.

3.5. Control section (without fiber)

The control section was a conventional full-depth reworking of the existing roadbed using 2 percent cement. The control section was built on the following day without equipment delay issues. The cement sacks were placed in two rows at a good spacing but without staggering. The cement sacks were not opened, and they were run over with the reclaimer, which tends to leave a streak of cement or blotches of cement along the path of the reclaimer about one bag wide. The assumption was that when the windrow was worked back and forth across the section with the maintainer, the blade would evenly distribute the cement.

3.6. Density measurements

A nuclear density gauge was used by the TxDOT maintenance crew to measure in-situ density at a 6-inch (152.4 mm) depth below the completed and compacted base surface, as shown in Fig. 18. Densities and moisture contents were measured at five locations for each test section, including control, FDR, and new sandstone base. The approximated spacing between nuclear density test locations 100ft (30.48m), with a starting location at 50 ft (15.24m). Table 5 summarizes the results measured by the nuclear density gauge.

Anderton et al. (2008) showed that the density and moisture in a field should meet the 90 percent measured dry density and ± 2 percent OMC criteria [20], according to ASTM 2006 1557. As can be seen in Table 5 and Fig. 19, overall field construction results were found to achieve good compaction and OMC. However, in the field, it seems that the difference in the amount of fibers used affects the density of the mixture as a whole. As a result, for the Paris District new base sandstone, the compaction effect was slightly lower than other sections containing 0.4 percent fiber due to the addition of 0.6 percent fiber.

3.7. Falling weight deflectometer (FWD) testing

In cooperation with the Paris District, FWD tests were collected on (a) January 23, 2020—before construction, (b) March 9, 2020—1-week after construction, and August 7, 2020—5-month after construction. FWD tests were conducted on the same location with the same setup for both before and after constructions. The goal was to evaluate the differences between before and after construction. FWD tests were conducted in both wheel paths (inside and outside) in northbound directions at a spacing of 30ft (9.144 m). Thus, a total of 102 FWD tests were performed in the 1,500-ft (457.2m) long section. Fig. 20 illustrates FWD testing near a visible patch for the before test section construction.

For easy comparison, maximum (W1) deflections were normalized to 9,000 lb (4082 kg). The maximum (W1) deflections for inside and outside wheel paths were averaged and grouped together. Fig. 21 presents the comparisons of maximum (W1) deflections between before and after fiber-reinforced base constructions. The limits of control, FDR, and new sandstone base sections are labeled in Fig. 21. As shown in Fig. 21, the normalized W1 deflections for the control section (without fiber) were lower 1-week after construction. However, for the FDR and new

sandstone base sections (with fiber), the normalized W1 deflections increased 1-week after construction. Note that there was a construction delay of approximately 5 hours for FDR and new sandstone base sections (with fiber). Because of unexpected construction equipment failure that caused compaction delays, cement was in contact with moisture for approximately 5 hours before compaction. Increased deflections for fiber sections are believed to be due to compaction delays. Guthrie et al. (2009) and Mujedu et al. (2016) documented that compaction delays have detrimental effects on strength and bearing capacity. Thus, lab tests were conducted to evaluate the impacts of compaction delays on UCS. The results are presented in the subsequent section [21,22].

Fig. 18. Nuclear Density Testing on Top of New Sandstone Base Section (2% Cement+ 0.6% Fiber).

Fig. 19. Measured dry density in test sections.

Table 5
Density and moisture content by nuclear density (1ft = 0.3048m).

Measurement location		Required	50 ft (15.2 m)	150 ft (45.7 m)	250 ft (76.2 m)	350 ft (106.7 m)	450 ft (137.2 m)	Average
Control section	Dry density (pcf [kg/m ³])	119.8 [1919.2]	118.1 [1892.0]	119.1 [1908.0]	120.7 [1933.6]	120.6 [1932.0]	120.8 [1935.2]	119.86 [1920.2]
	Percent density achieved (%)	100	98.6	99.4	100.8	100.6	100.9	100.06
	Moisture content (%)	10.5	9.5	9.4	11.5	11.8	10.2	10.48
FDR section	Dry density (pcf [kg/m ³])	119.8 [1919.2]	117.9 [1888.8]	112.7 [1805.5]	118.9 [1904.8]	119.5 [1914.4]	121.6 [1948.0]	118.12 [1892.3]
	Percent density achieved (%)	100	98.4	94.1	99.2	99.7	101.5	98.58
	Moisture content (%)	10.5	10.4	10.6	10.5	9.3	8.5	9.86
New base section	Dry density (pcf [kg/m ³])	132.2 [2117.8]	123.5 [1978.5]	125.1 [2004.1]	123.1 [1972.1]	118.5 [1898.4]	122.5 [1962.5]	122.54 [1892.3]
	Percent density achieved (%)	100	93.4	94.6	93.1	89.6	92.7	92.68
	Moisture content (%)	6.7	9.7	7.8	8.3	8.2	8.3	8.46

Fig. 20. FWD testing on FM897 before.

Fig. 21. Comparisons of FWD maximum (W1) deflections between before and after test section construction.

Fig. 22. Effects of compaction delay on UCS reductions.

As shown in Fig. 21, it is very encouraging to find that there were significant reductions on the normalized W1 deflections at 5 months after construction. In particular, the FDR and new

sandstone base sections (with fiber) experienced over 52 percent reduction as compared to 1 week after construction FWD data. Furthermore, the averaged W1 deflections were lower than before construction for both FDR and new sandstone base sections (with fiber). This indicates that there were rapid increases in structural capacity and significant strength developed in the fiber sections between 1 week and 5 months. Further research is needed to explain the mechanism and phenomena.

3.8. Laboratory verification on compaction delays

To study the effects of compaction delays on UCS, six specimens were prepared using the new sandstone base aggregates. Six specimens with duplicates were compacted after 30-minute, 3-hour, and 5-hour delays, as shown in Fig. 22. Those six specimens were cured for 7 days before the UCS tests. All six specimens were prepared with a mix of cement of 2 percent and fiber content of 0.6 percent (Fibermesh 300). As shown in Fig. 22, the 5-hour compact delay caused a 55 percent reduction on UCS. The US Army Corps of Engineers [3,13,14] suggested that 30 minutes is an absolute maximum allowable time to complete compaction once cement is in contact with moisture.

4. Observations and conclusions

The observations and conclusions are given as follows:

1. The laboratory UCS results showed significant improvements (>112.36 percent) when fibers were added to the sandstone base provided by the Paris District.
2. Based on lab test results, three test sections with fiber were constructed on FM 897 in the Paris District. To have better control, fiber and cement were manually distributed, following the US Army Corps of Engineers' recommendations.
3. Because of unexpected construction equipment failure that caused compaction delays of approximately 5 hours, cement was in contact with moisture for approximately 5 hours before compaction. Field FWD test results showed increased deflections after construction.
4. Lab verification tests were conducted in May 2020. UCS results showed an approximate 55 percent reduction when there was a 5-hour delay from the time water was introduced (resulting in the start of the hydration process) until the time of compaction. It indicated that there are detrimental effects on UCS if there is delay on compaction.
5. There were significant reductions on the normalized W1 deflections at 5 months after construction. In particular, the FDR and new sandstone base sections (with fiber) experienced over 52 percent reduction as compared to 1 week after construction FWD data. Furthermore, the averaged W1 deflections were lower than before construction for both FDR and new sandstone base sections (with fiber). This indicates that there were rapid increases in structural capacity and significant strength developed in the fiber sections between 1 week and 5 months. Further research is needed to explain the mechanism and phenomena.
6. It will be critical to use construction procedures and full-size equipment that would be viable for major projects involving miles of pavement. Such procedures must include mechanized distribution of chemical and fiber stabilizers since manual placement—as used on previous test sections—is unrealistic for pavement jobs that are miles long.

Acknowledgements

This work could not have been completed without the assistances of Wade Blackman, Jerry Hale, Boon Thian, and Shelley Pridgen of Texas Department of Transportation.

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